Institute for Laser Technology

Thermal analysis of cryogenic Yb:YAG TRAM laser for high-average power systems

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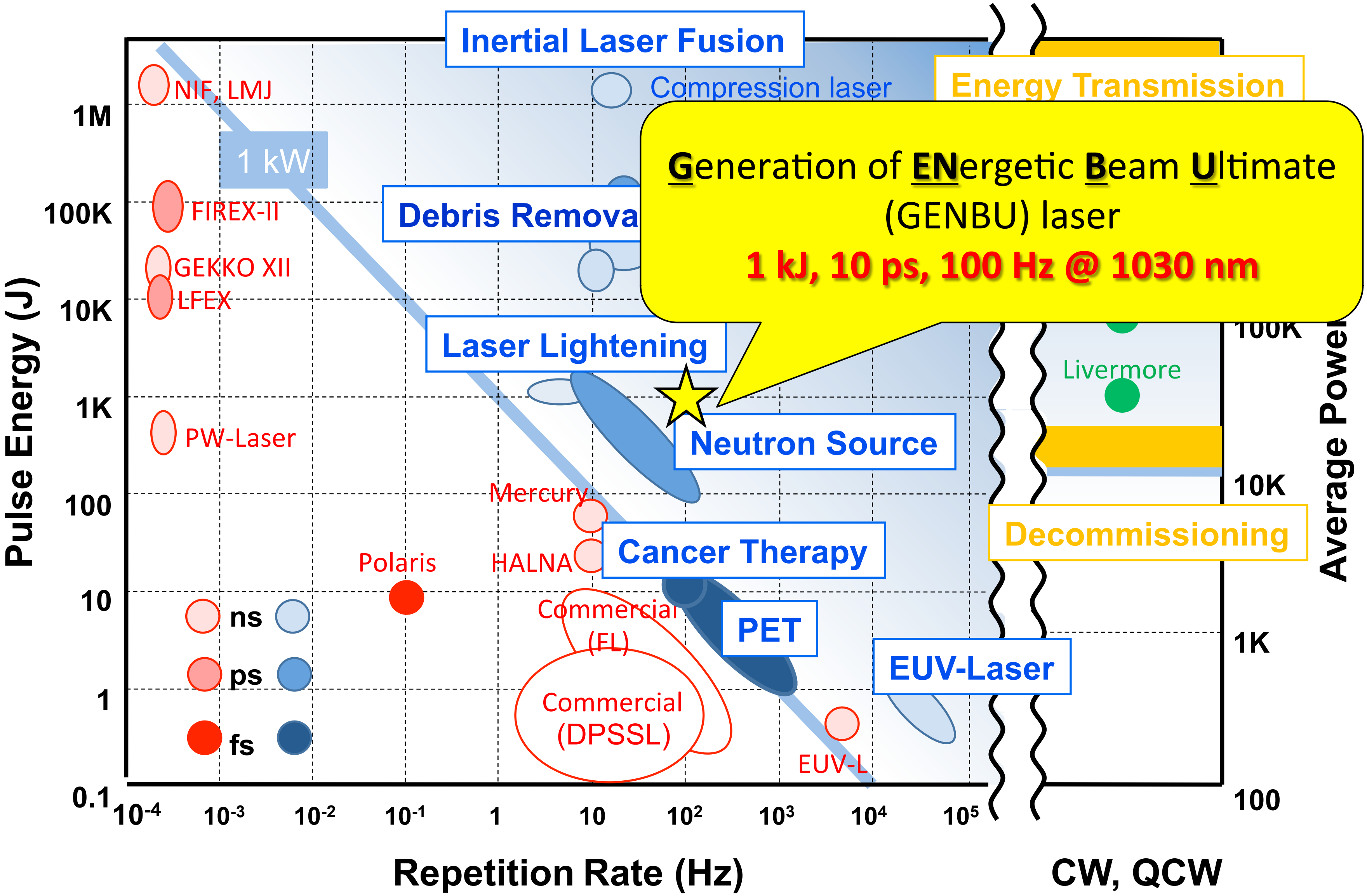
Applications for Next Generation High Energy Lasers



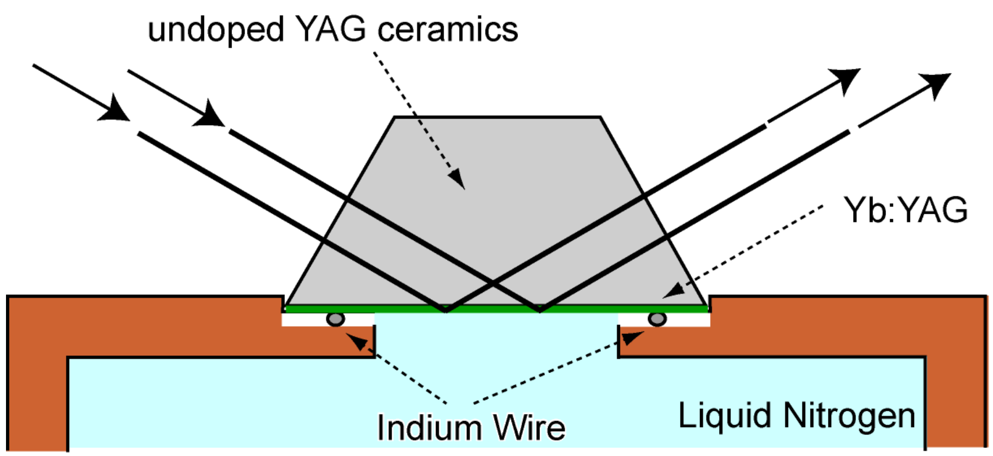
Introduction

Objective: Output power > 10 kW, High Efficiency, High Quality

Issues: Thermal Problems, Damage, etc…

Approaches:

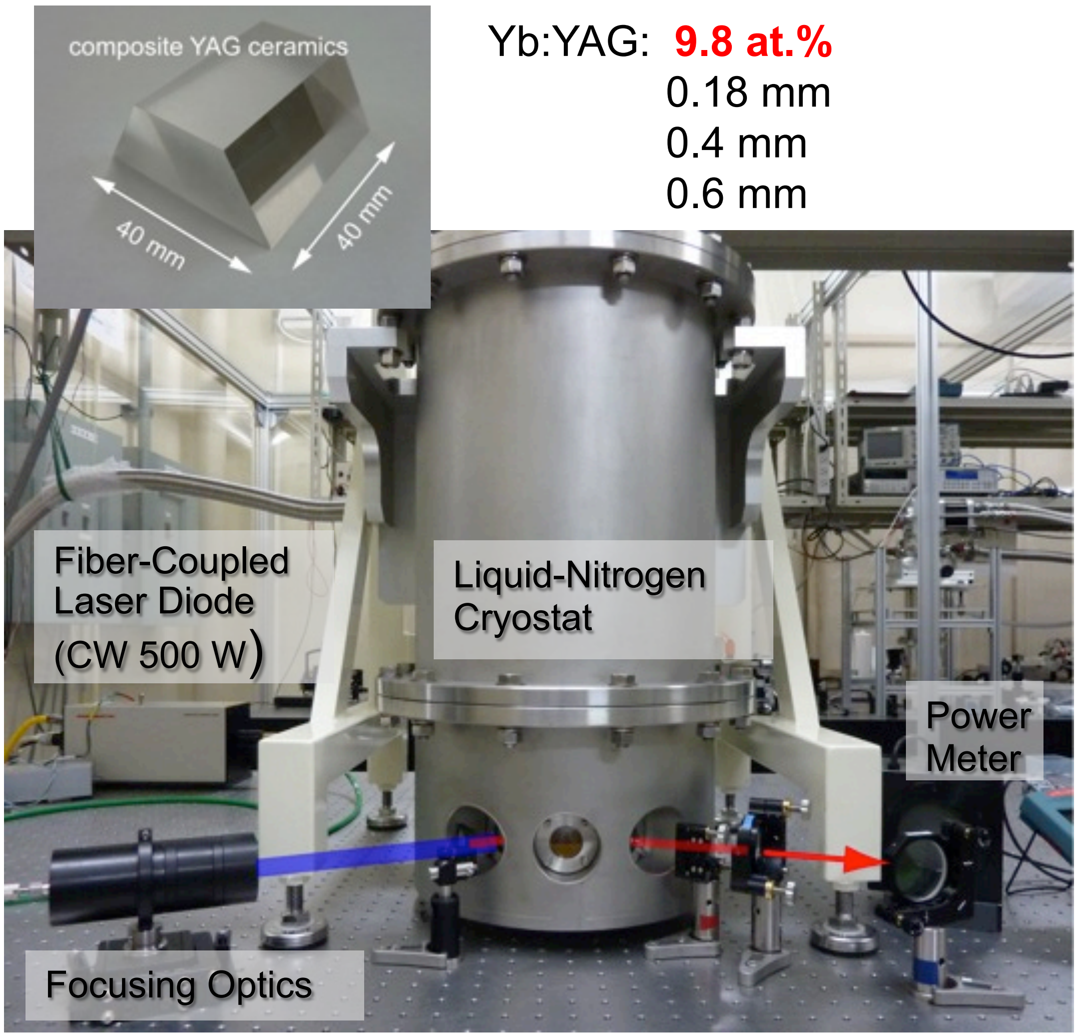
- Cryogenic Yb:YAG Ceramics (< 100 K)
  → Efficient 4-level operation, improved thermal properties
- Total-Reflection Active-Mirror (**TRAM**)
  → Without HR coating、LN_2 directly cooling



High power multi-transverse mode TRAM Oscillator

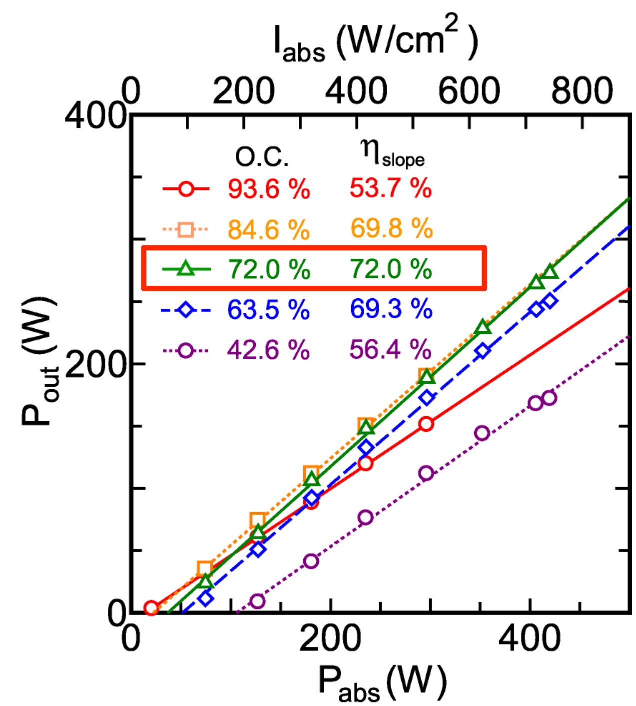
Konoshima Cemical Co. Ltd.

Yb:YAG: **9.8 at.%**
0.18 mm
0.4 mm
0.6 mm



H. Furuse, *et al*, *Opt. Lett*. 34, 3439 (2009).

Yb:YAG : d = 0.4 mm



Multi-transverse mode

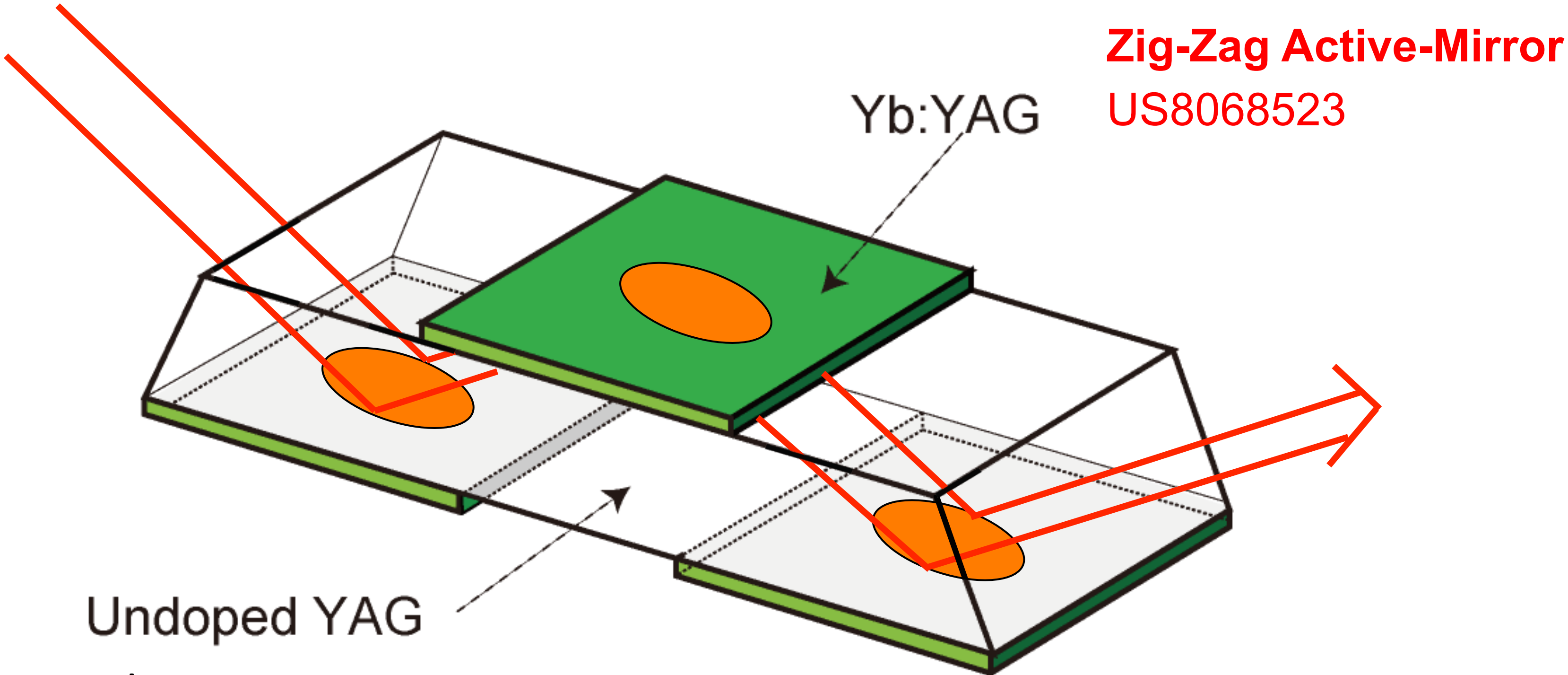
Output : 273 W

Optical Effi. : 65%

Slope Effi. : 72%

Pump Intensity : 0.75 kW/cm^2

Combining multi-TRAMs for 10 kW class laser power



Power Scaling

Enlarged pump area + Serially arranged multi-TRAMs

Design Concept

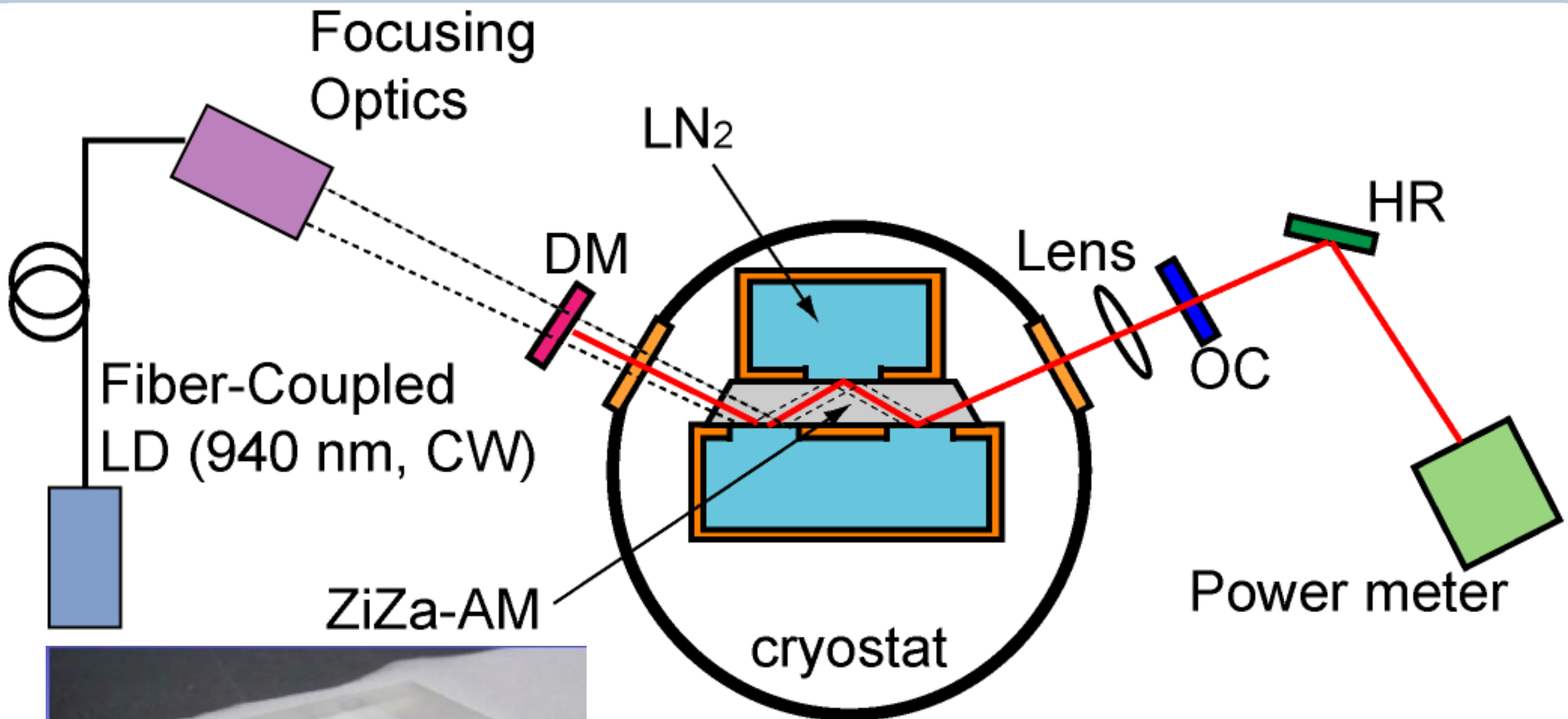
» Each temperature rise is almost the same with thickness and doping.

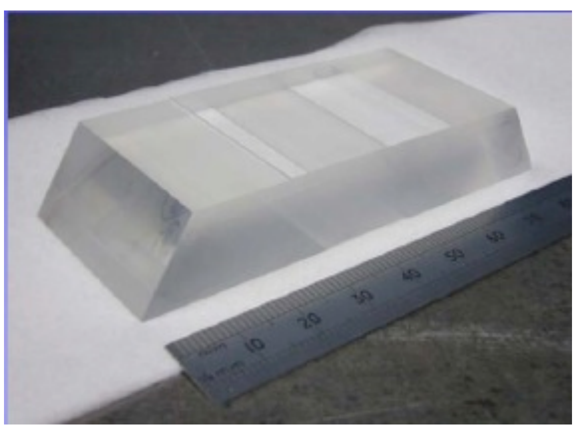
» More than 95% of the pump beam can be absorbed.

⇨ *10 kW class Laser Oscillator* (for Industries)

500 W class Laser Amplifier System (for Pulse Operation, CPA)

Experimental Setup for ZiZa-AM Laser Oscillation





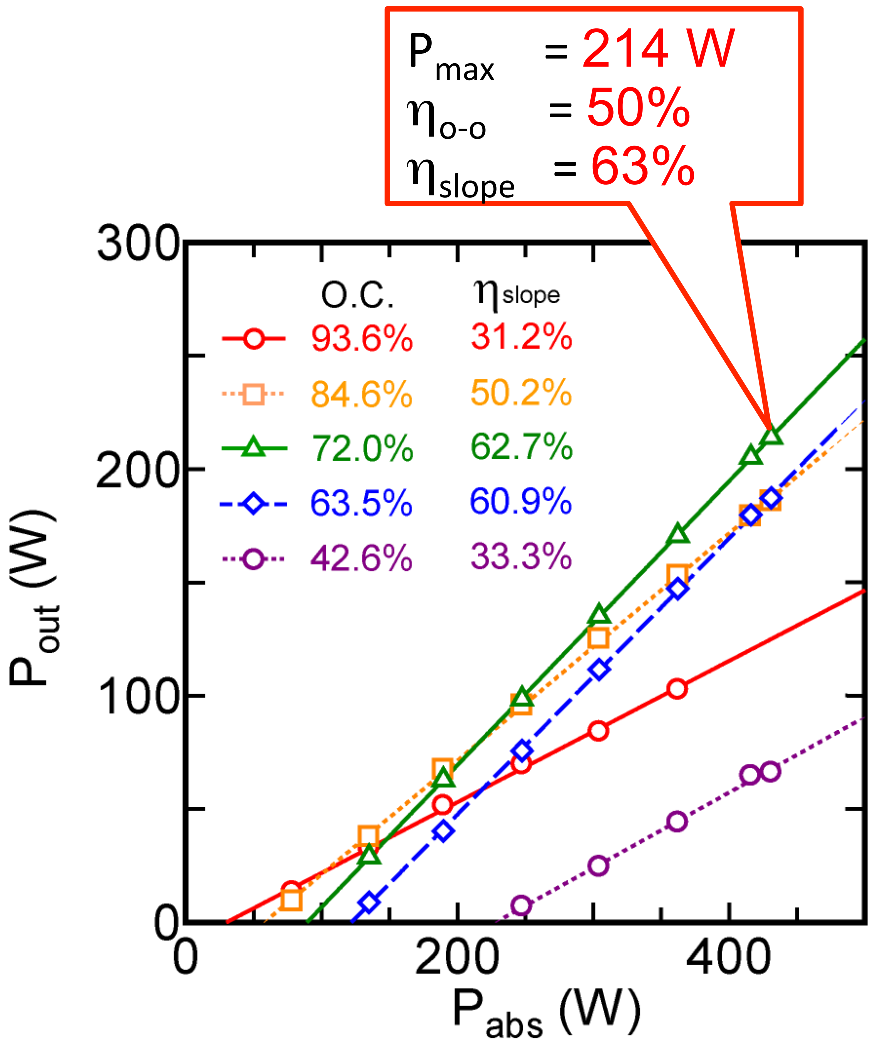
3 Yb:YAG disks

Konoshima Cemical Co. Ltd.

- CW 500 W LD was used as a pump source. → **431 W** was absorbed in ZiZa-AM.
- Pump beam was focused onto each Yb:YAG disk at **9 mm, 8 mm, and 9 mm**, respectively.

Experimental Results of ZiZa-AM Laser

Multi-transverse mode



H. Furuse, *et al*, *Opt. Exp.* 19, 2448 (2011).

- We have obtained **214 W** with **50%** optical efficiency and **63%** slope efficiency. These were lower than the TRAM results.

··· **Because…**

- The absorbed **pump intensities are very low** (142, 169, 63 W/cm^2).
- The beam coupling may be poor.

Both of the laser power and the optical efficiency **will be improved** with more powerful pump source. Now, we are preparing more powerful pump LD to achieve kW class power.

Approaches for higher performance

Multi Transverse Oscillation → MOPA System

- Study of TRAM Amplification Characteristics

  (Small Signal Gain, ASE/Parasitic Lasing, Temperature rise, Wave-front Distortion, Birefringence Losses, etc …)

  → ***For several-kW laser systems***

  (10 J and 100 Hz, 100 J and 10 Hz)

- 10 kW laser system based on ZiZa-AM concept.

  → ***For 10-kWclass laser systems***

  (100 J and 100 Hz, 1 kJ and 10 Hz)

Thermal Analyses

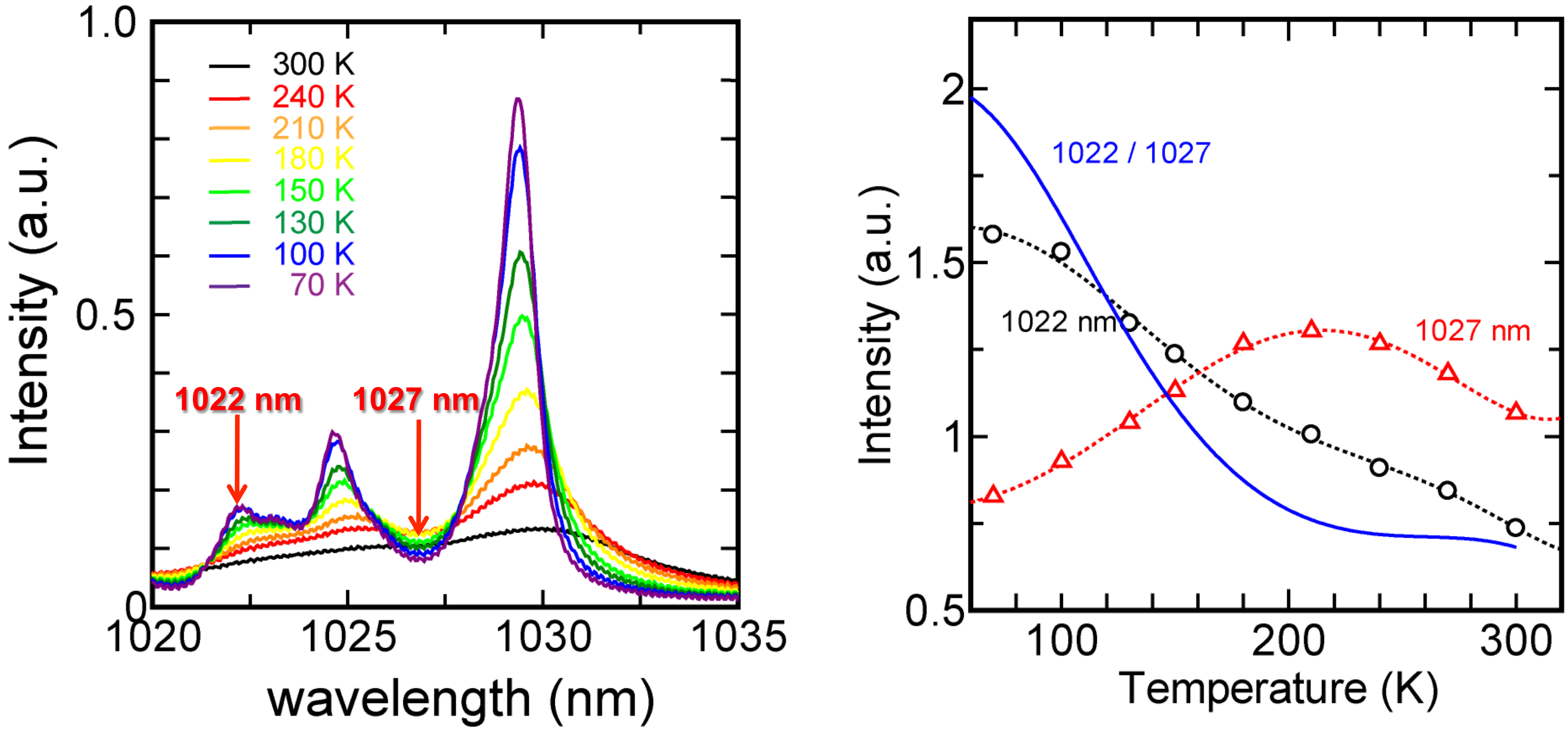
Experimental

- Temperature Rise
- Wavefront Distortion
- Thermal Birefringence

Theoretical

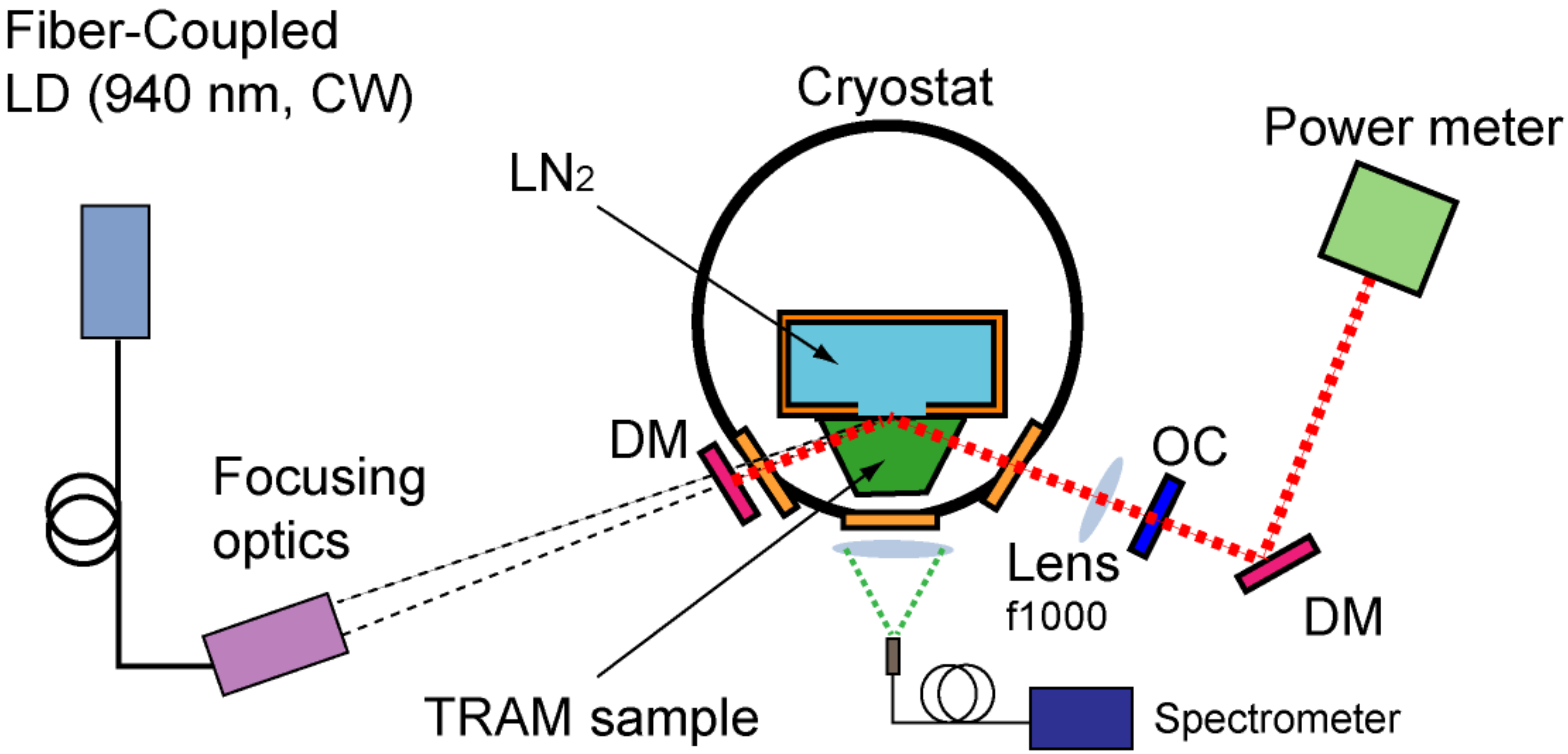
- 3D Thermal Distribution
- Thermal-Stress Distribution
- Ray Trace

Estimation of Yb:YAG Temperature



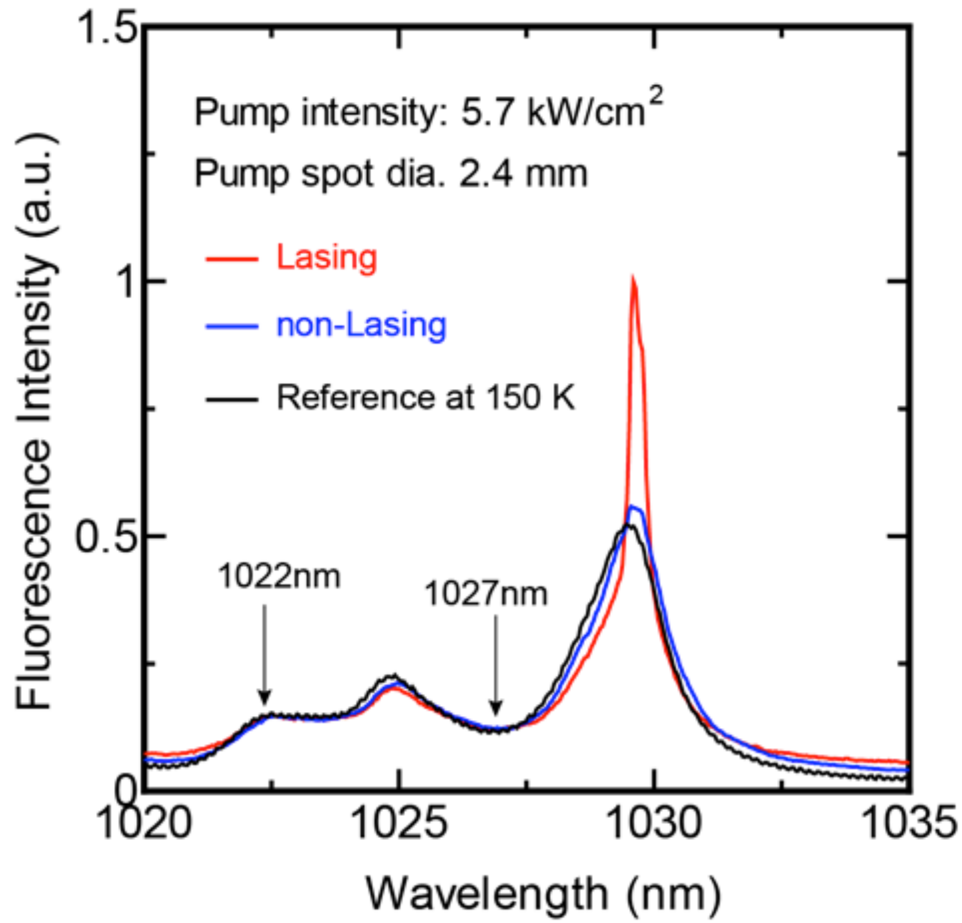
- Yb:YAG temperatures were inferred by comparing with temperature controlled fluorescence spectra which are measured by a thin Yb:YAG ceramics with low pump power to exclude re-absorption effect and temperature rise.

Experimental setup for temperature rise



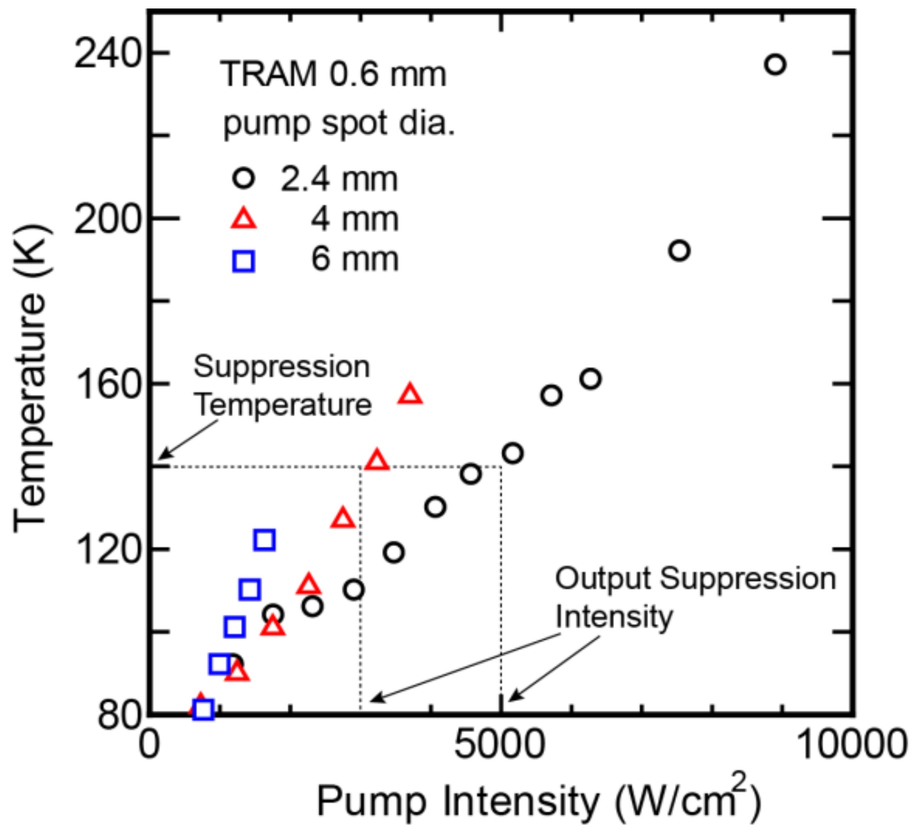
- Fluorescence spectra were also measured by a spectrometer.
- These experiments were performed under lasing and non-lasing conditions.

Comparison of fluorescence spectra at high pump intensity



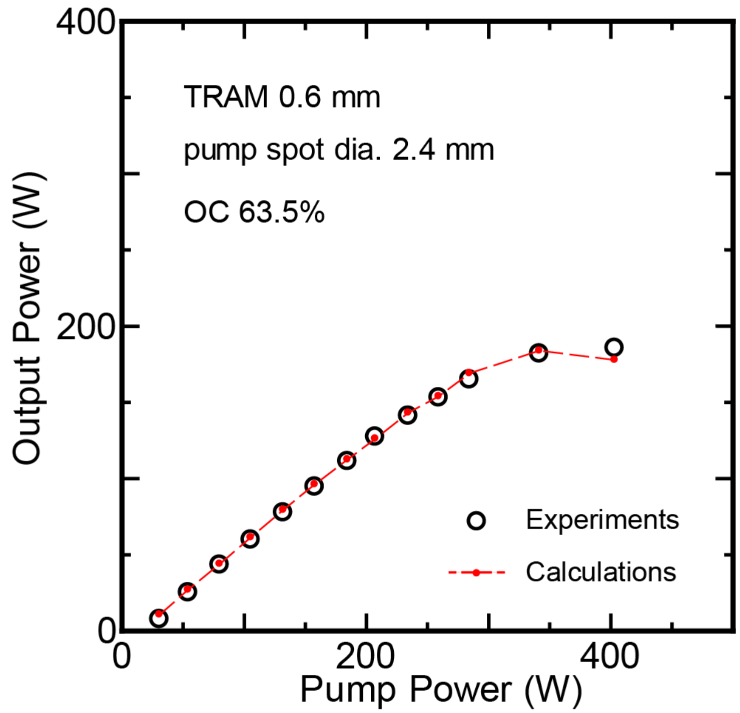
- There is a discrepancy between spectra at 1029.5 nm due to the lasing and amplified spontaneous emission, however, fluorescence intensities at 1022 nm and 1027 nm are invariant.

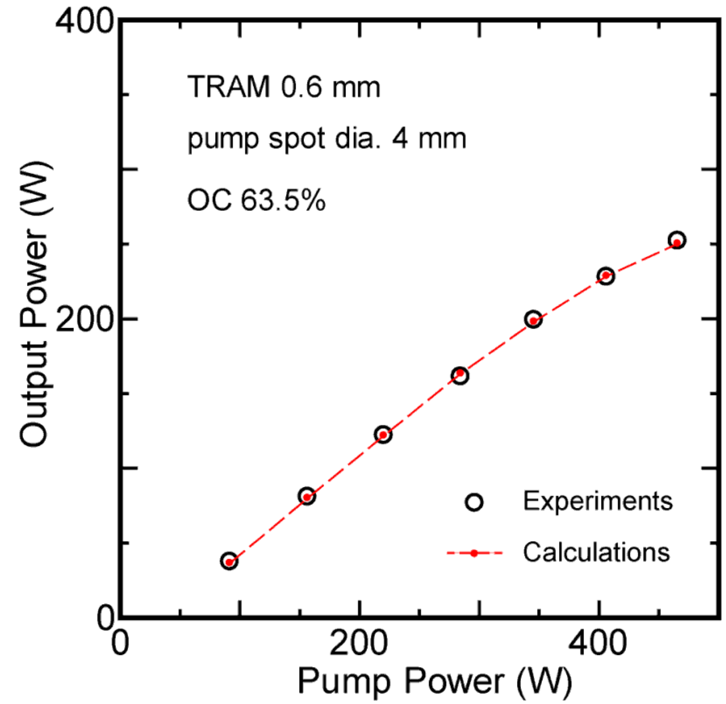
Temperature Rise of 0.6mm-thick TRAM



- Yb:YAG temperature is lower for the smaller pump sot size under the same pump conditions. This is because the cooling efficiency is higher for smaller pump spot size due to omni-directional cooling.

Output characteristics for 0.6 mm-thick TRAM



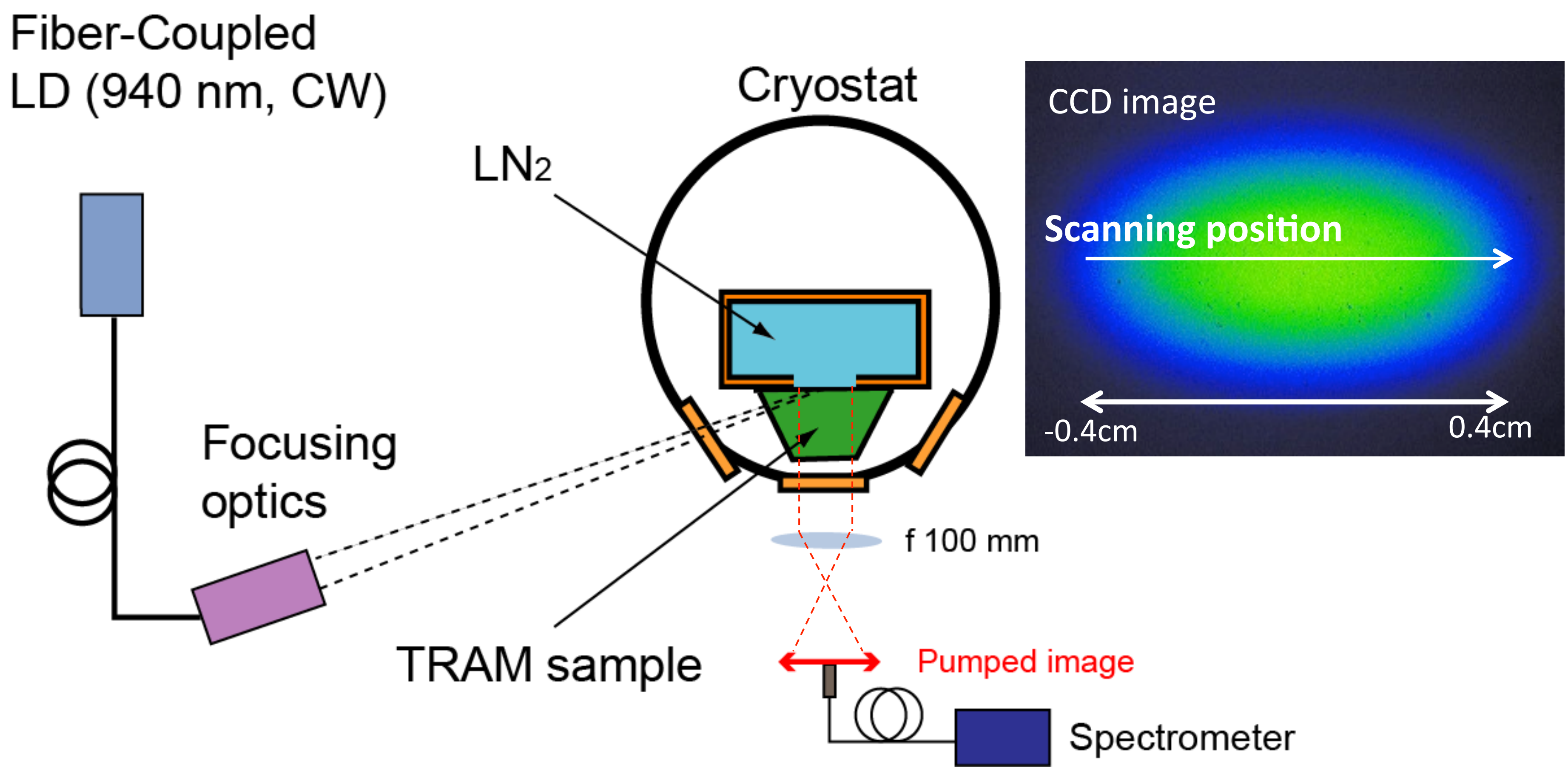


$$P_{out} = \frac{I_s(T)S}{2}\left(\frac{1-R}{1+R}\right)\left(\frac{2g_0(T)l}{\delta - \ln R + 2\alpha'(T)l} - 1\right),$$

$$g_0(T) = \sigma_{emi}(T)\tau_f \eta_Q \eta_S \eta_a \eta_B \frac{1}{h\nu}\frac{P}{V},$$

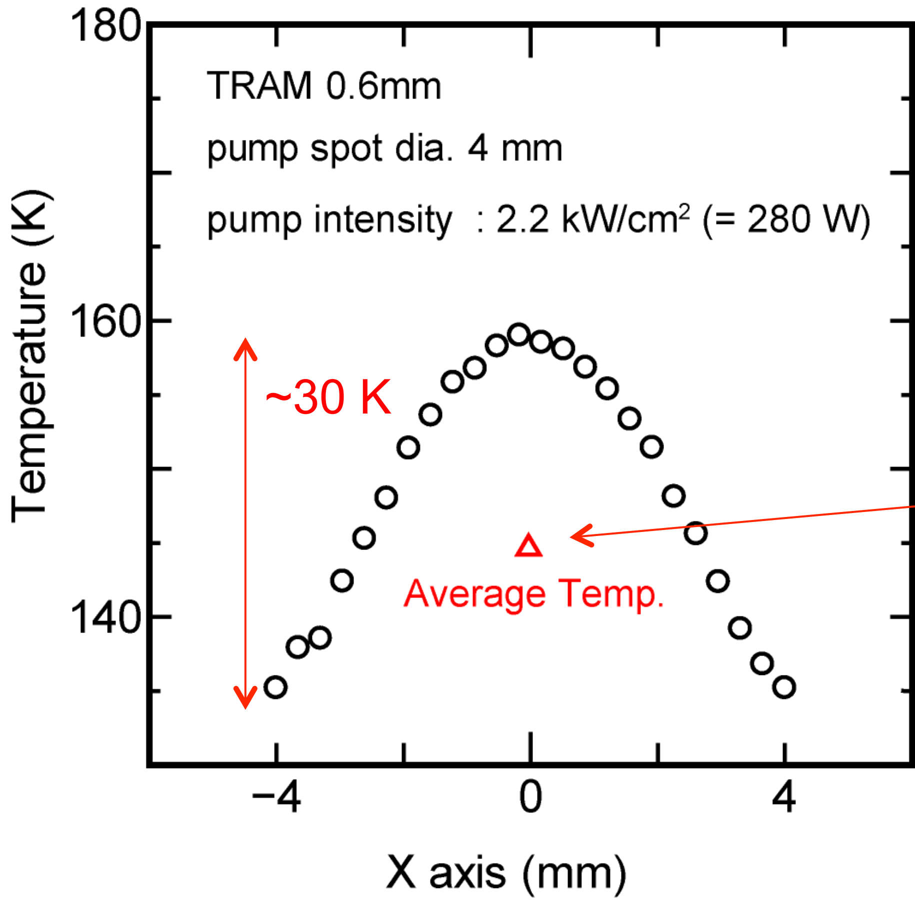
H. Furuse, *et al*, *Opt. Exp.* 20, 21739 (2012).

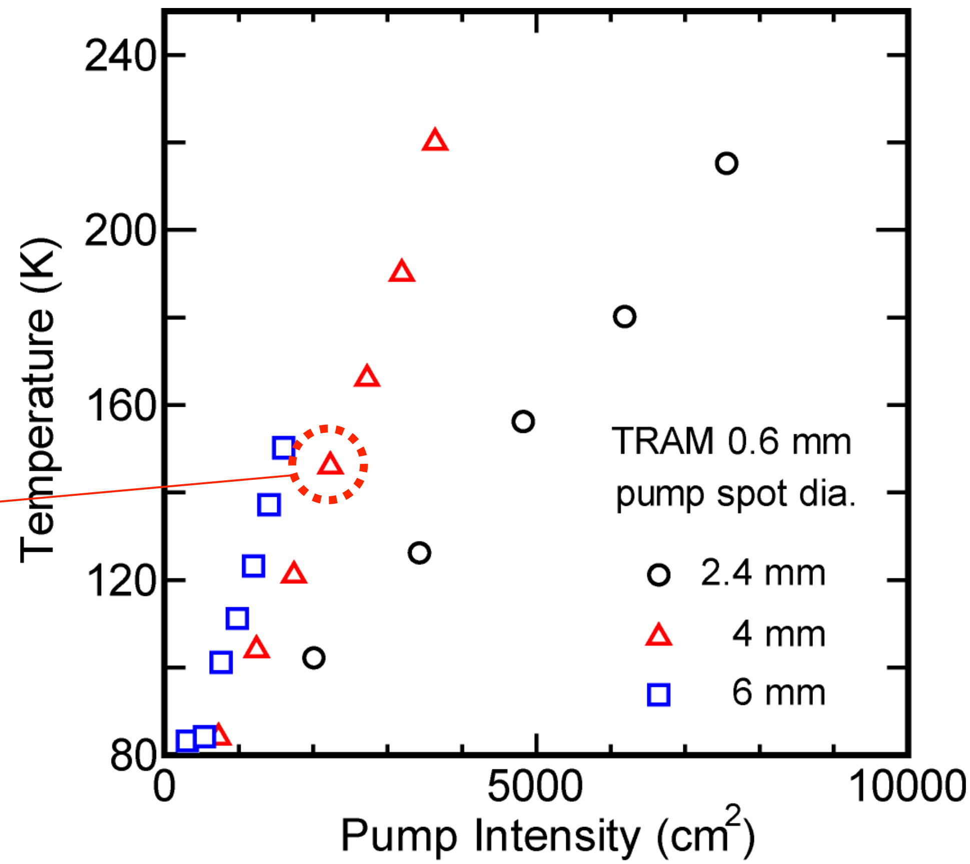
Thermal Distribution



- To study the thermal distribution in Yb:YAG layer, we expanded an image of the pumped area, and measured the fluorescence spectra by scanning the position.
- The pump spot diameter was 4 mm, and the pump intensity was 2.2 kW/cm^2.

Thermal Distribution (non-lasing case)



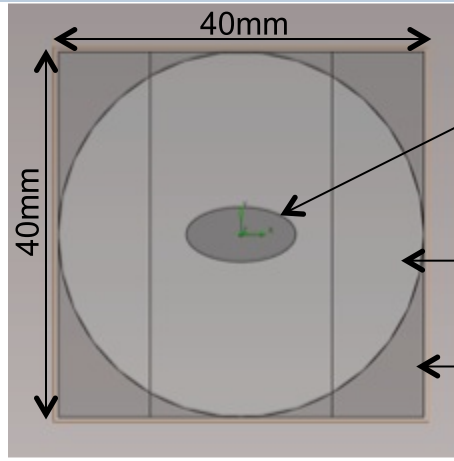


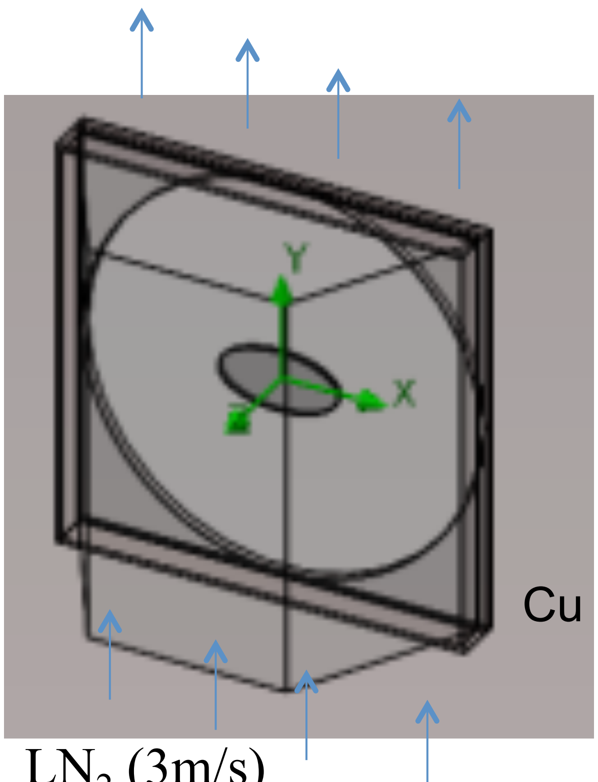
- We can see the thermal distribution in the Yb:YAG layer, and the temperature difference in the layer is about 30 K.
- The calculated temperature from a sum of the spectra approximately shows the average temperature.

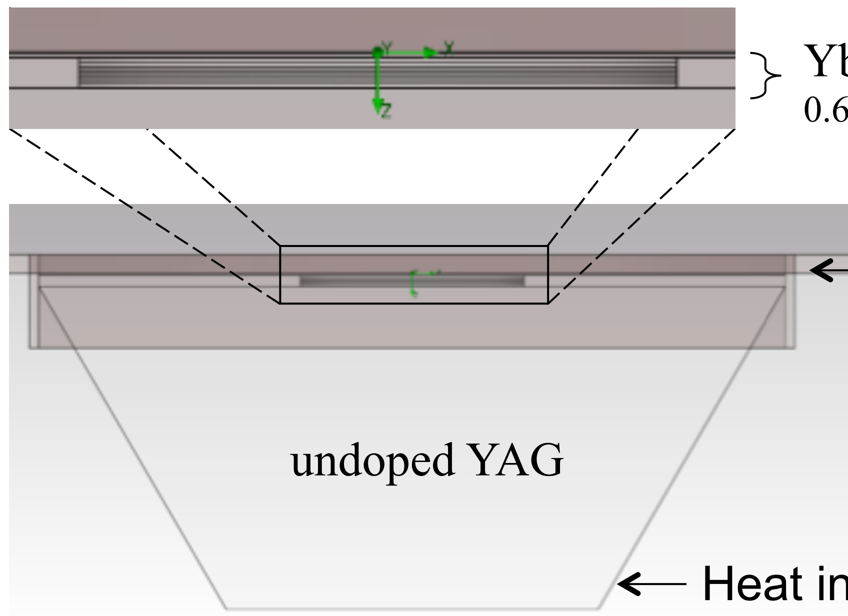
Calculation Model

Finite Element Method

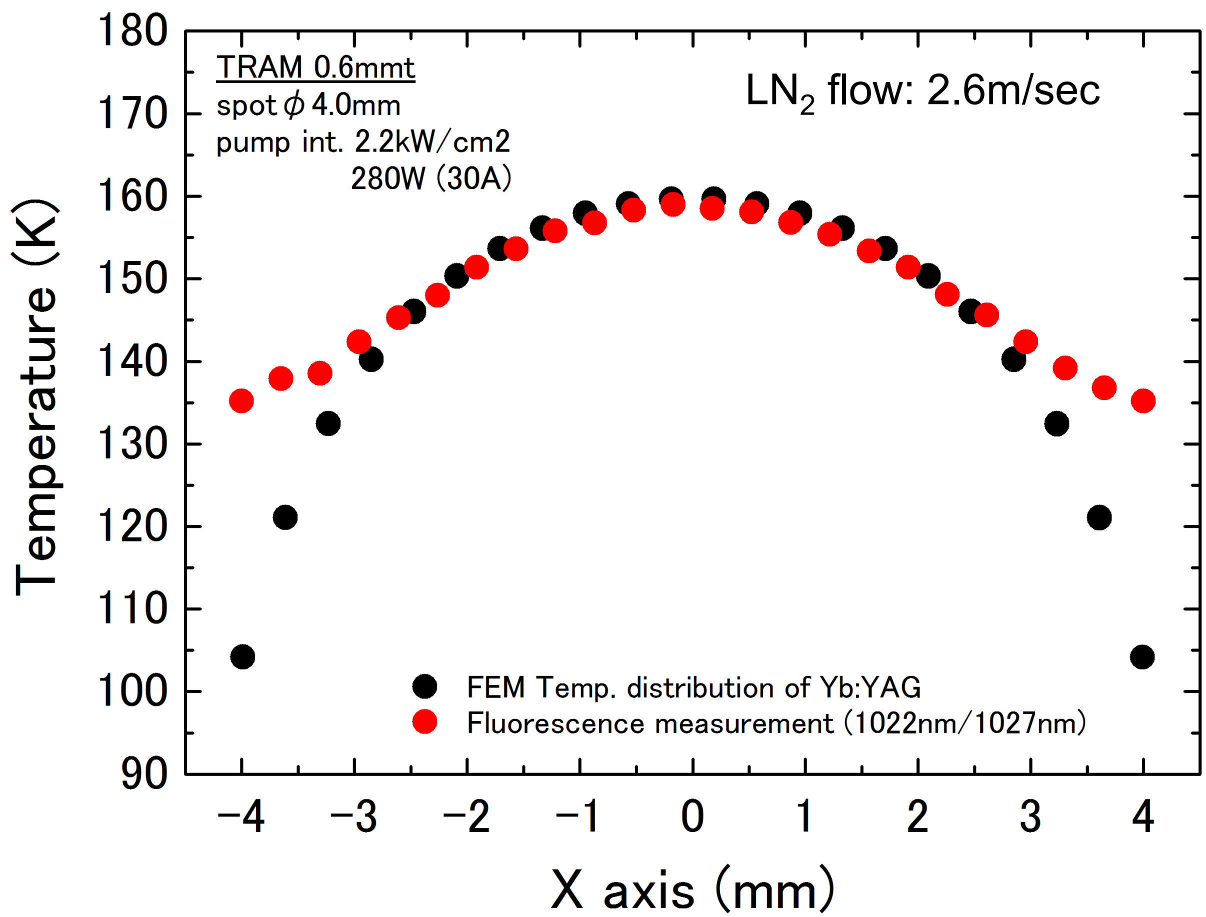
- Mesh : ~ 1 million
- $K(T)$ for undoped and doped YAG
- Coolant : LN_2
- Heat generageion effi. : 20%







Comparison between Experiments and Calculations



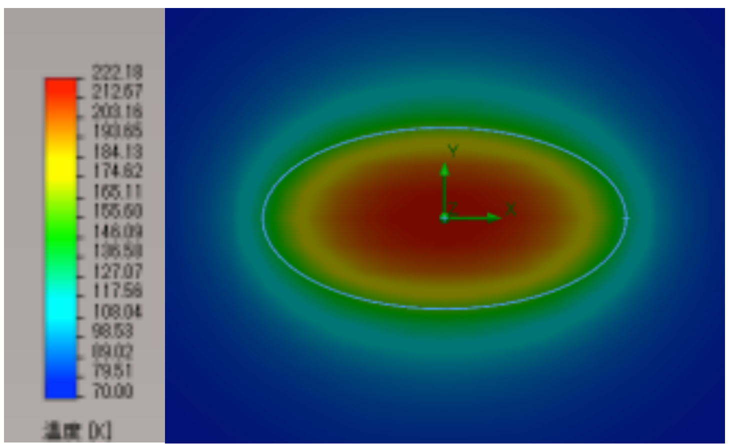
- The calculated temperature distribution in the Yb:YAG layer using FEM shows a reasonable agreement with experiments.
- In the calculations, the heat transfer coefficient was 8600 W/m^2K.

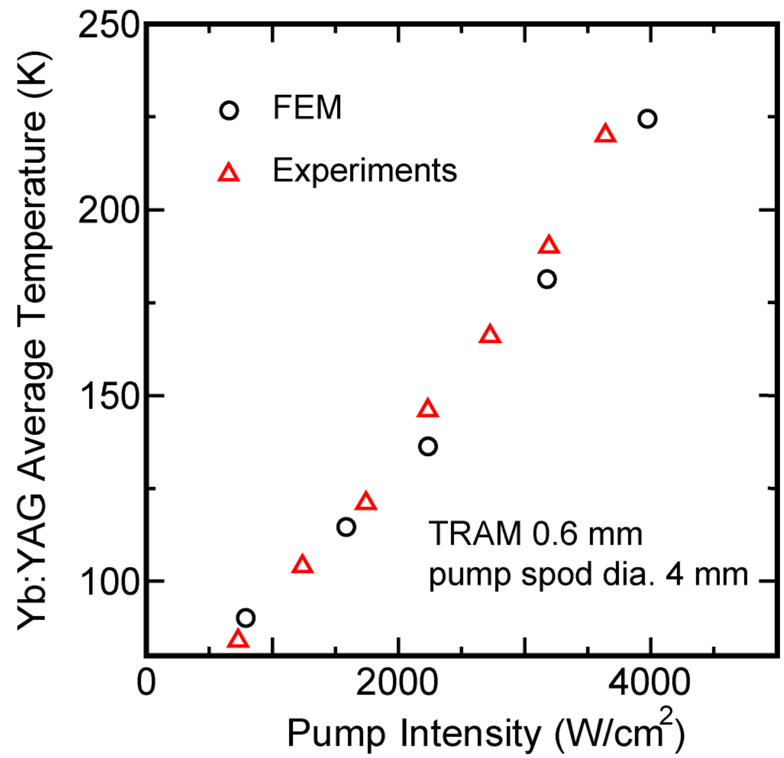
Calculated Results and Comparison with experiments

Temperature of Yb:YAG (FEM)

Pump dia. : φ4.0mm
Pump intensity : 1~5kW/cm^2
LN_2 flow speed : 2.6 m/s

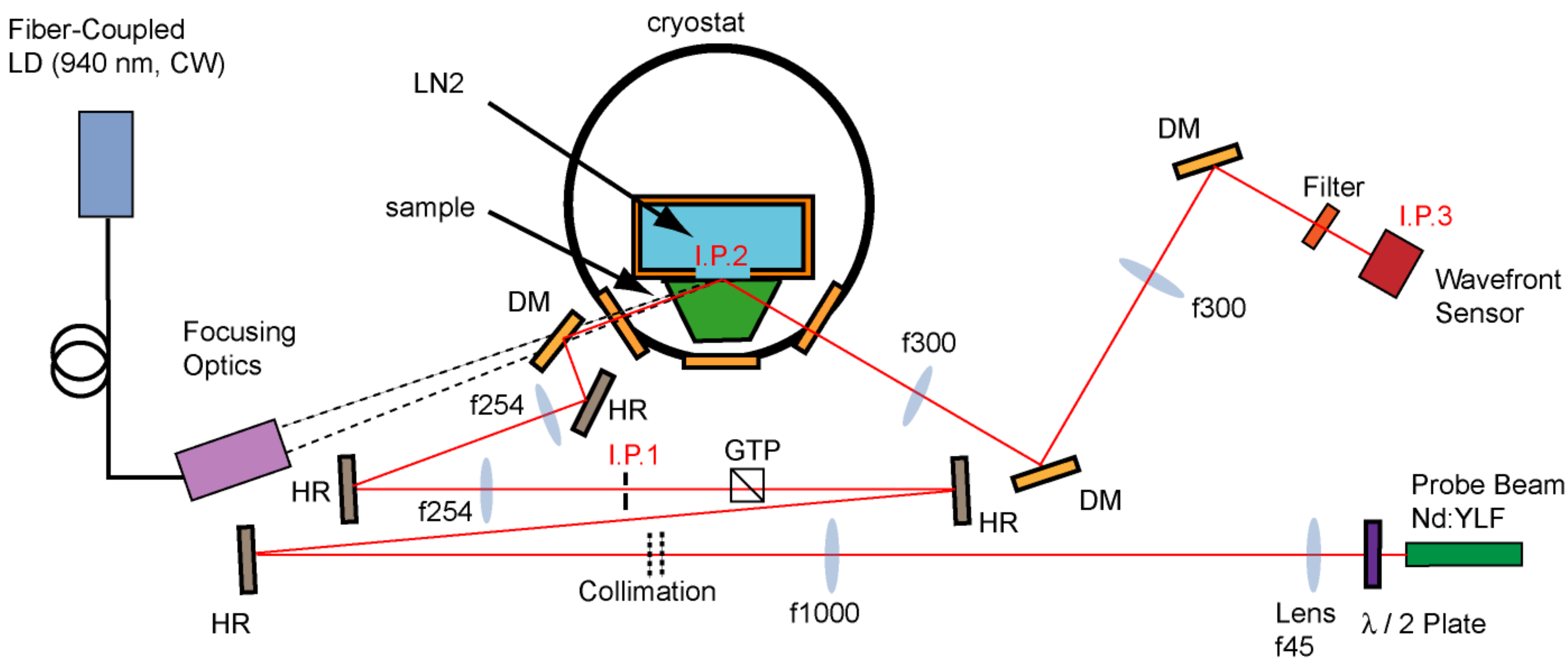
example : 1.8kW/cm^2





- The average temperature from FEM calculations were good agreement with experiments, and we could explain the Yb:YAG temperature from calculations.
- We will calculate the Yb:YAG temperature for the case of enlarging pump, for increasing the output power.

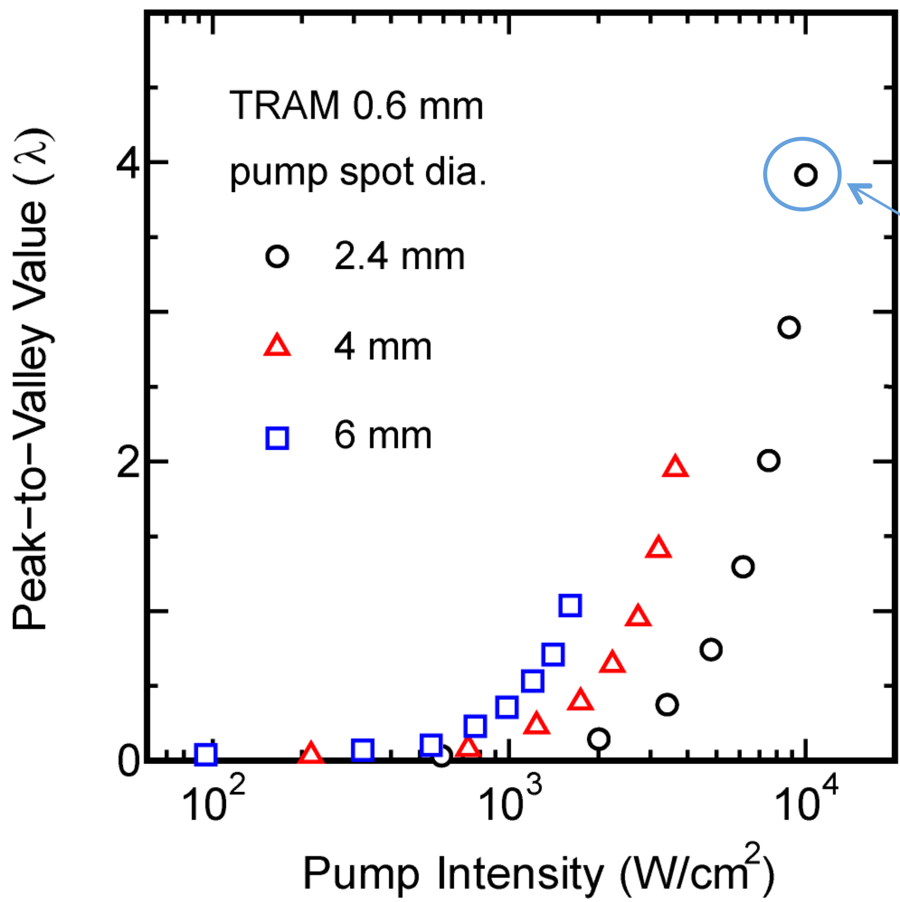
Wave-front Measurement Setup

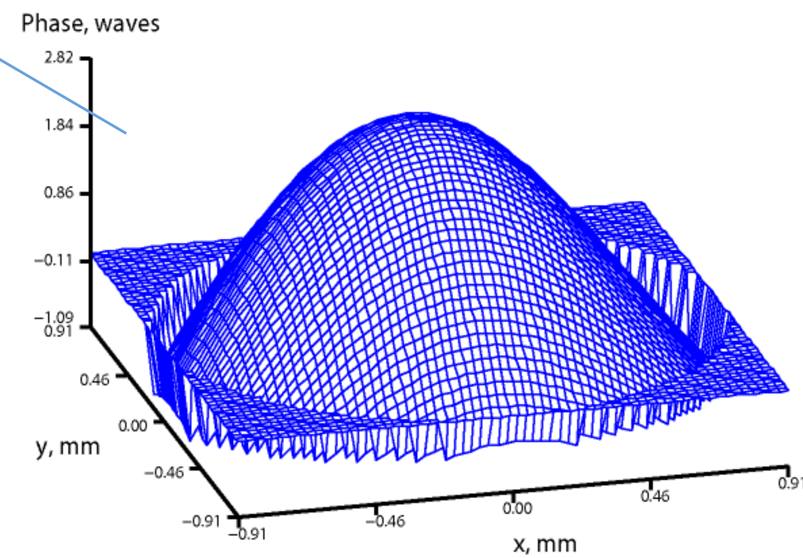


- A Fiber-Coupled LD (CW 500 W, 940 nm) was used as a pump source, and a linearly polarized Nd:YLF laser (CW 70 mW, 1054 nm) was used as a probe beam.
- Pump beam spot diameter on Yb:YAG TRAM was ~ 2.4 mm, 4 mm or 6 mm.
- A wavefront of the transmitted beam was measured by **Shack-Hartmann wavefront sensor**.

Wave-front Distortion of 0.6 mm-thick TRAM

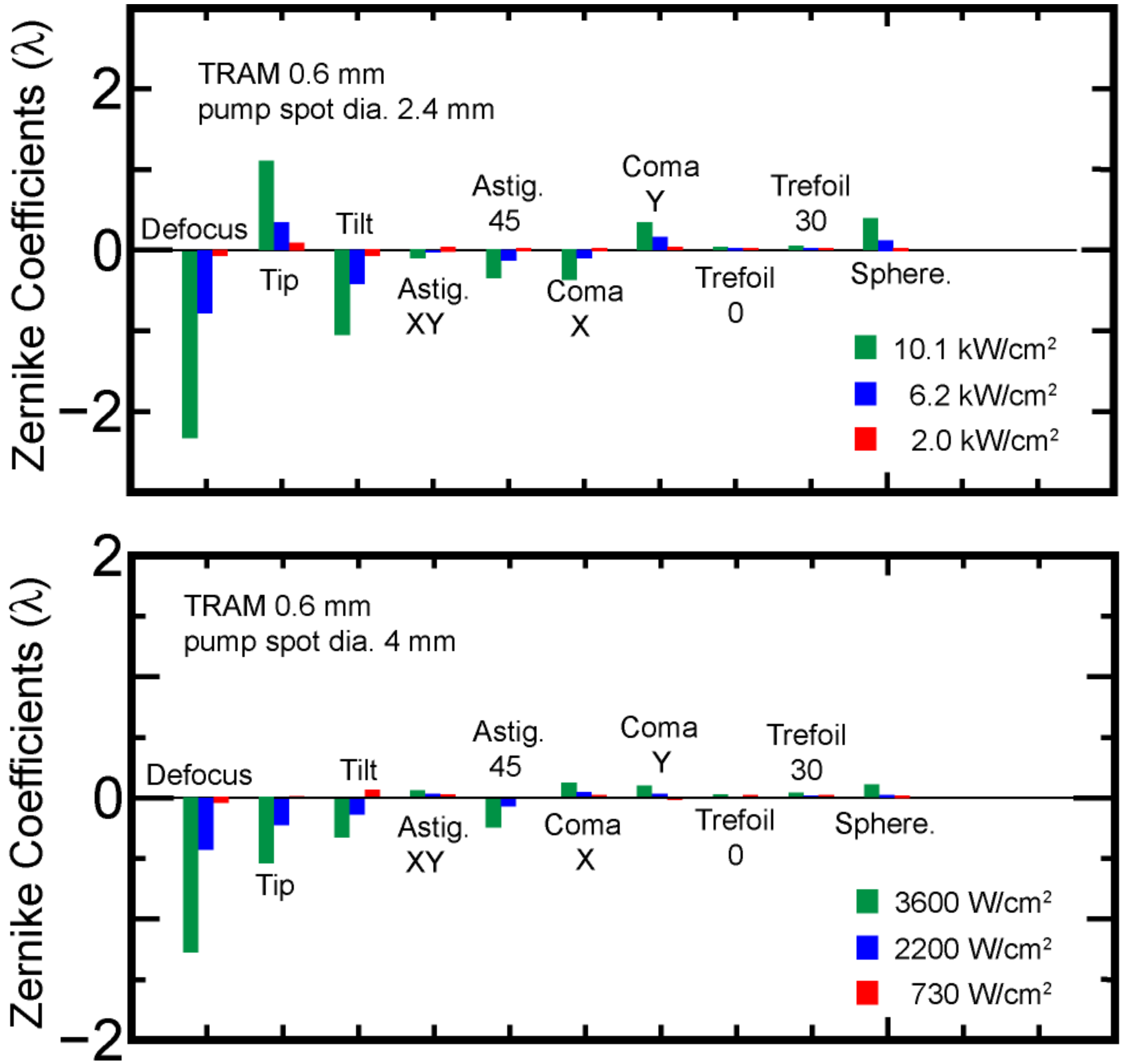
TRAM 0.6mm,



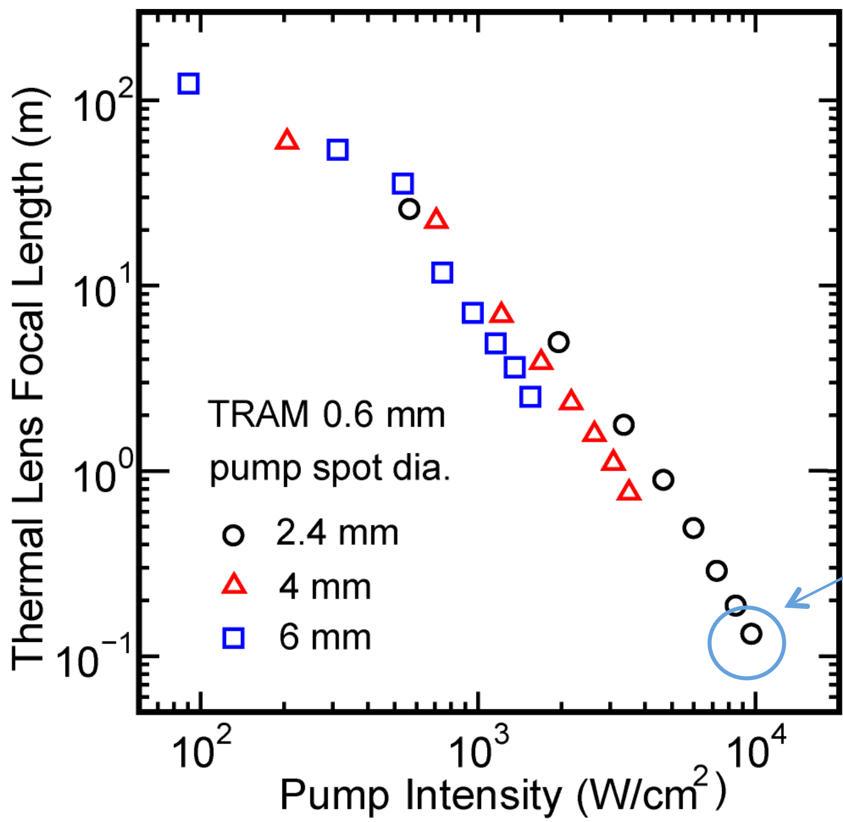


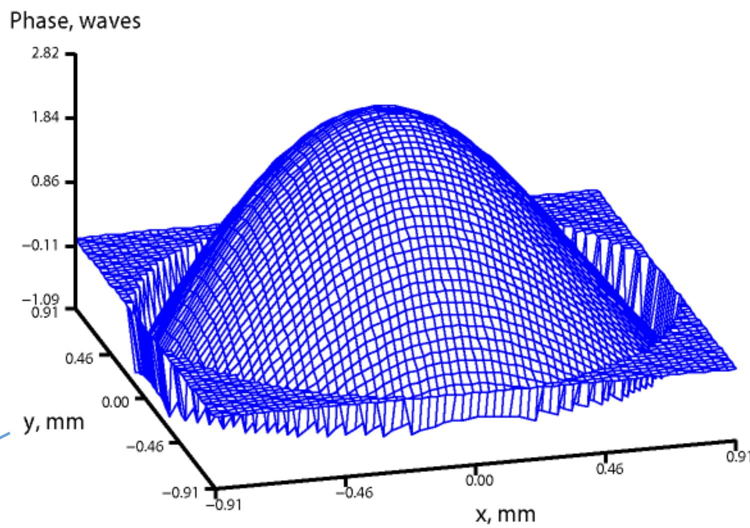
- The transmitted wave-front was measured using a Shack-Hartmann sensor.
- Peak to valley value was over 4 λ at the highest pump intensity (10 kW/cm^2).

Zernike Polynomials



Wavefront Distortion and Thermal Lens Effect

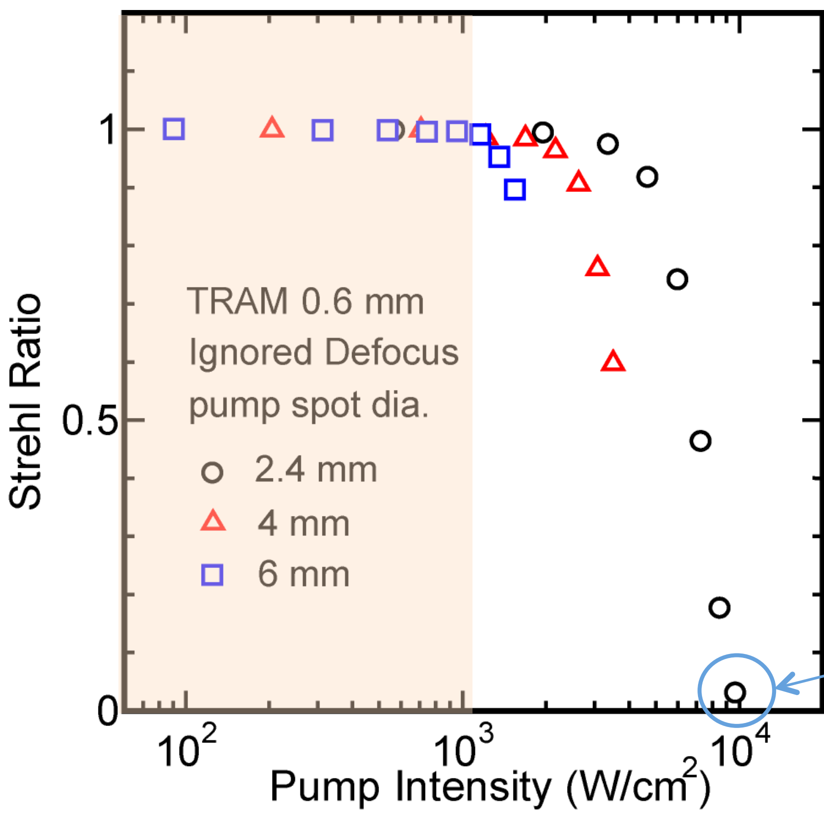




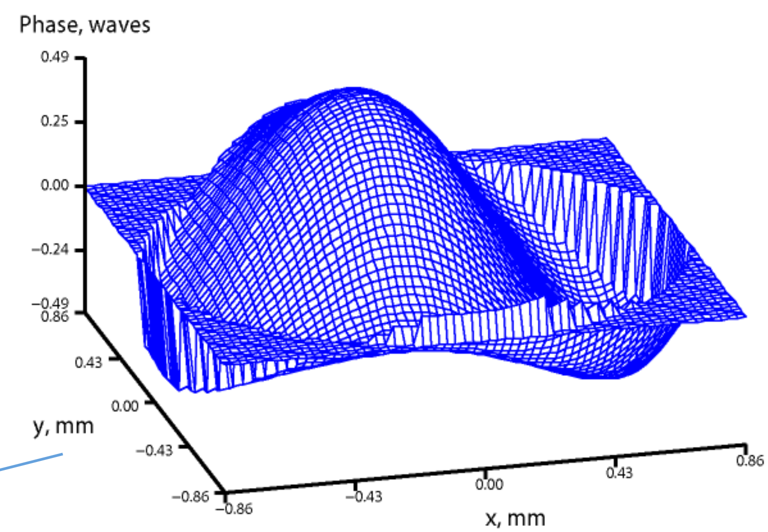
f ~ *130 mm*

- The phase distortion at the wave-front sensor is expanded on Zernike polynomials, and the **thermal lens focal length** can be estimated.
- For 0.6mm thick TRAM, the strong thermal lens effect with *f* ~ 130 occurred.

Strehl Ratio and Wave-front Distortion ignoring Defocus

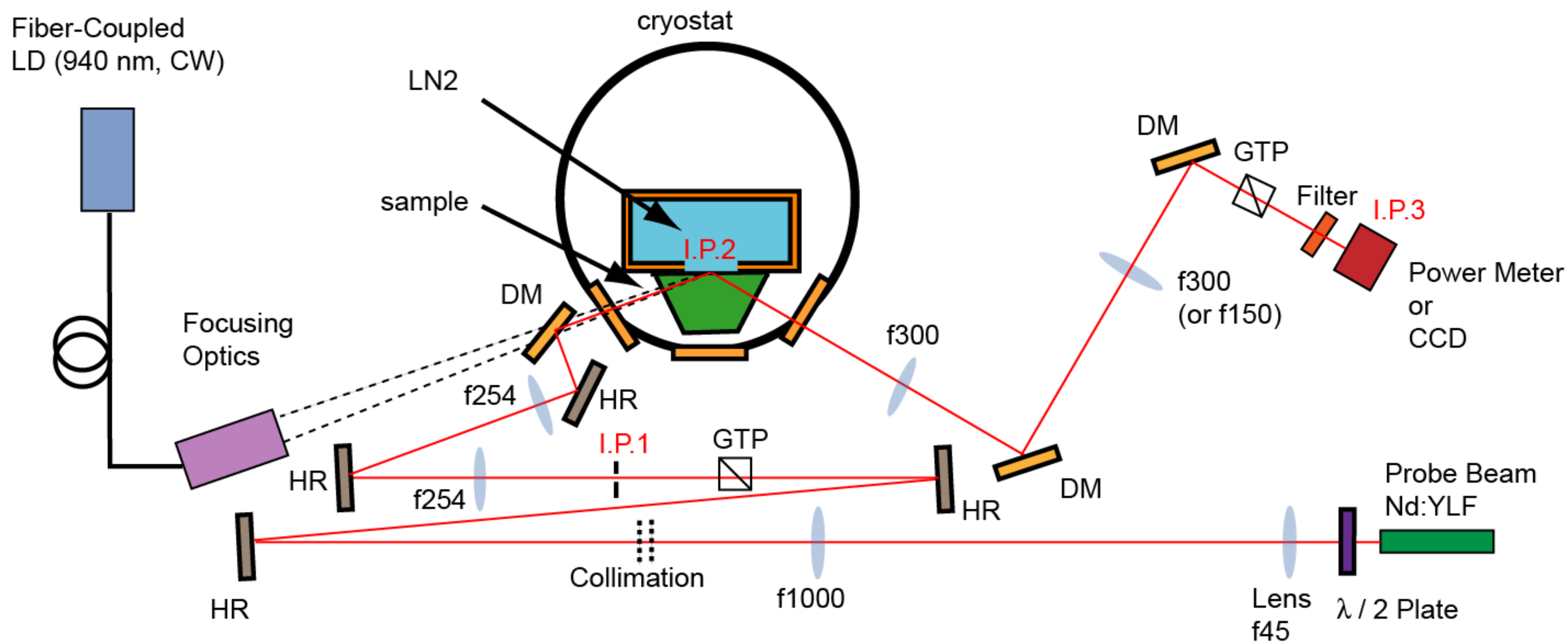


Ignored Defocus



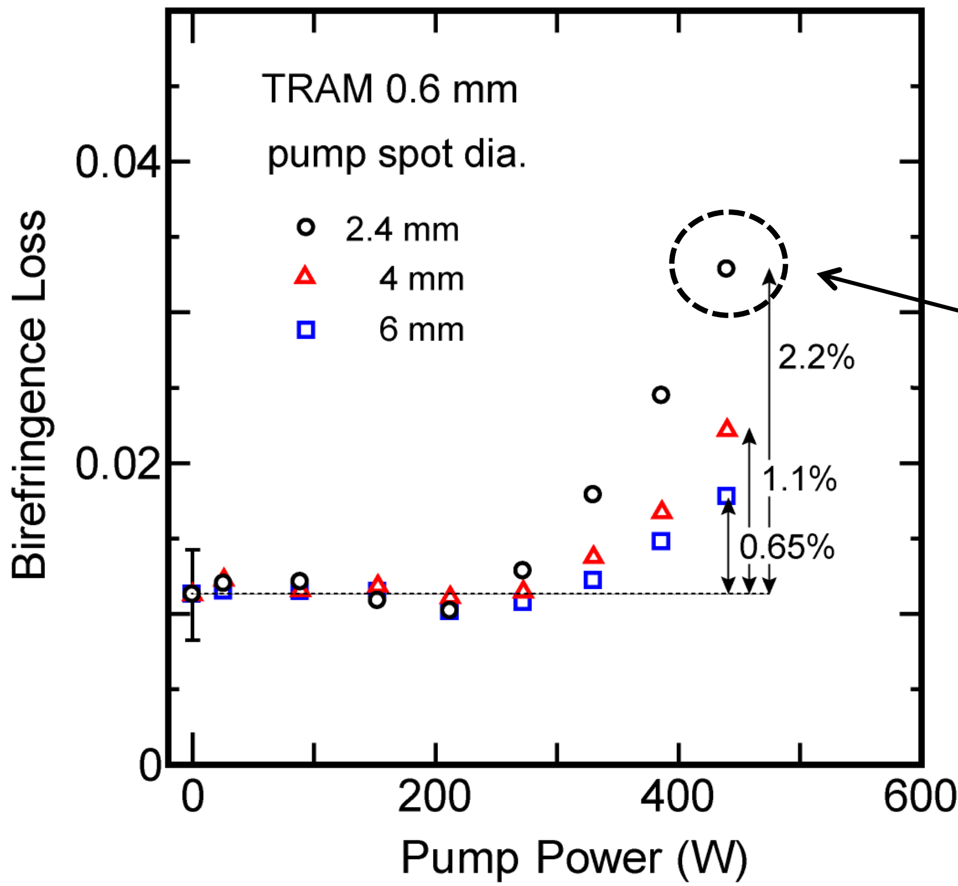
- Defocus component could be compensated by lenses.
- Other distortions need more sophisticated optical components such as deformable mirrors.
- A deformable mirror may not be necessary for up to 1,000 W/cm^2 pumping.

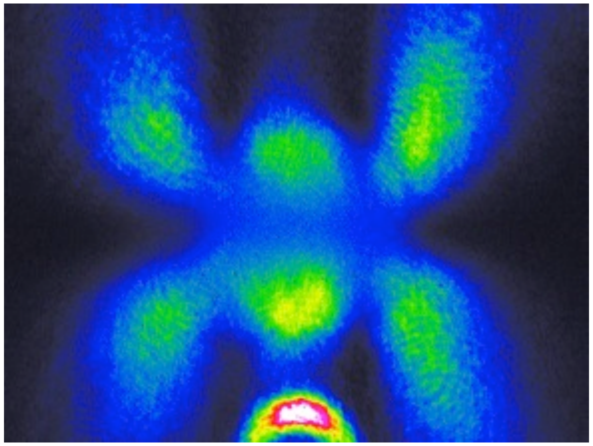
Birefringence Induced Loss Measurement Setup



- To measure the thermally induced birefringence loss, Glan-Thompson polarizer pair was used under the crossed Nicol condition.
- The leakage profile and power were measured by a CCD camera and a power meter.

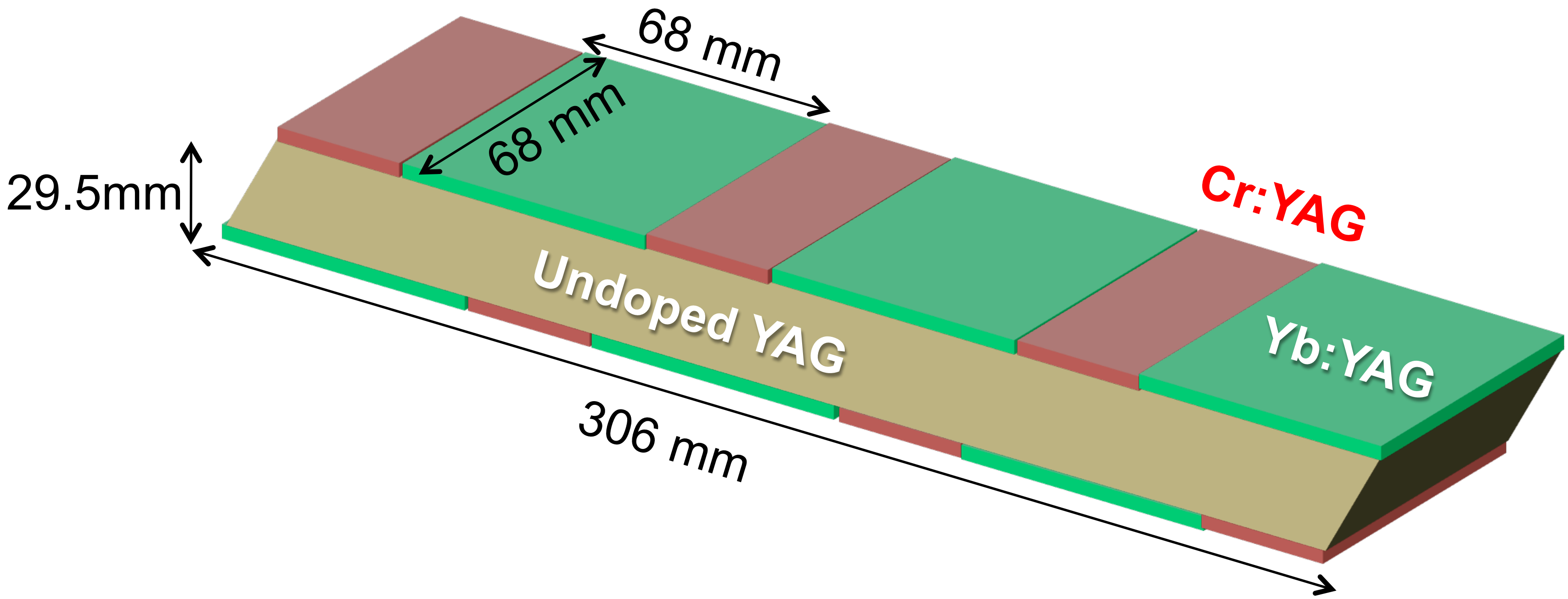
Thermally induced birefringence Loss





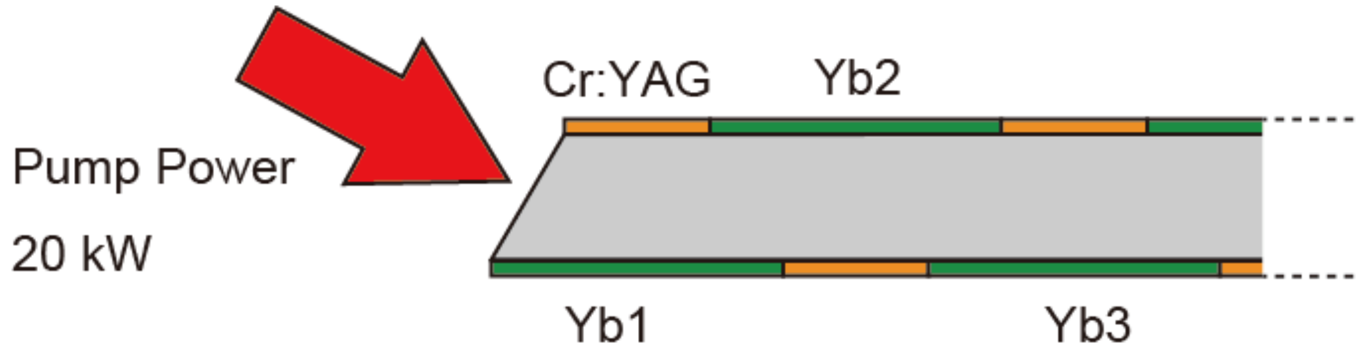
- A birefringence loss of ~ **2.2%** was observed at ~ 10 kW/cm^2 pump intensity.
- The leakage pattern looks like a butterfly (the detail is under investigation).
- Experimental results will be used to compare with FEM calculations.

Conceptual design for > 10 kW laser system



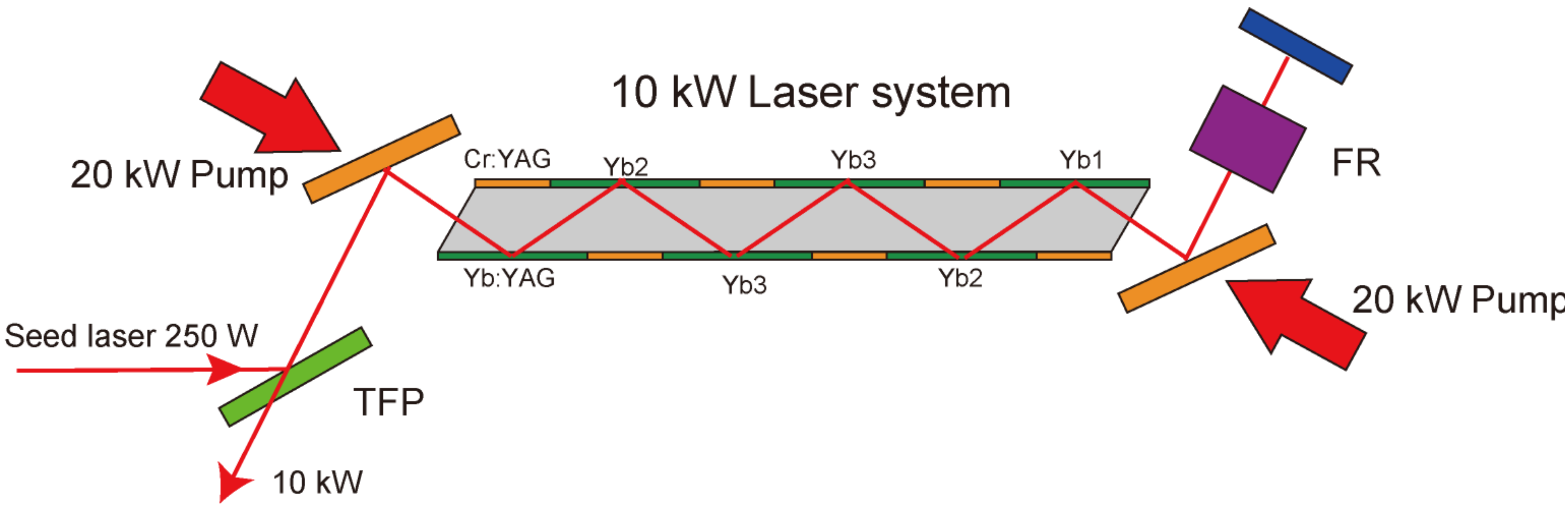
- This includes 6 Yb:YAG layers whose sizes are 68 x 68 mm^2, and Cr:YAG layers are used as an absorber to avoid ASE effect.
- Doping concentration and thickness of each layer are adjusted to satisfy
  - Absorption : 100%
  - ASE gain : $g_0 l_{ASE} < 4$
  - Absorbed pump Intensity : < 400 W/cm^2
  - temperature rise inside the Yb:YAG layer : $\Delta T < 15$ K.

Conceptual design for > 10 kW laser system



	Yb1	Yb2	Yb3	Requirements
Doping of Yb^{3+}	0.3%	0.7%	2%	
Yb:YAG thickness	2.6 mm	2 mm	2 mm	
Absorption	32.7%	34.8%	32.5%	100%
Absorbed pump power	6.5kW	6.9 kW	6.5 kW	
Absorbed pump intensity	141 W/cm^2	148 W/cm^2	141 W/cm^2	< 400 W/cm^2
ΔT	10.5 K	7.7 K	11.7 K	< 15 K
$g_0 l_{ASE}$	3.0	4.0	3.8	< 4.0
Small signal gain , ***G***	1.37	1.40	1.37	

Conceptual design for > *10 kW* laser system



- This can totally absorb **40 kW** of pump power and double pass gain will be $G > 40$. Output power of over **10 kW** (= 200 W/cm^2) can be possible using 300 W class seed source and double pass amplifier.

Summary

◆ Multi-transverse mode Oscillation

- TRAM ･･･ ･･････････････ P_{out} = 273 W, $\eta_{o\text{-}o}$ = 65%, η_{slope} = 72%
- 3-TRAMs (ZiZa-AM) ･･･ P_{out} = 214 W, $\eta_{o\text{-}o}$ = 50%, η_{slope} = 63%

◆ Amplification Characteristics (TRAM)

- Temperature Rise ････We obtained temperature distribution in Yb:YAG layer
- FEM ･･･We obtained reasonable agreement with experiments.
- Wavefront Distortion ･･･ Aberration free at I_{abs} < 400 W/cm^2
- Birefringence Loss ･･･ Thermally induced birefringence loss is about 2% at 10 kW/cm^2 pumping.

◆ Thermal analyses of 10 kW ZiZa-AM laser using FEM

- Thermal-Stress Distribution, Ray trace → Beam profile, power potential